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Gooding et al.

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(54) **INTERACTIVE TOOL FOR VISUALIZING PERFORMANCE DATA IN REAL-TIME TO ENABLE ADAPTIVE PERFORMANCE OPTIMIZATION AND FEEDBACK**

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(52) **U.S. Cl.**
USPC **715/736**

(58) **Field of Classification Search** 715/736
See application file for complete search history.

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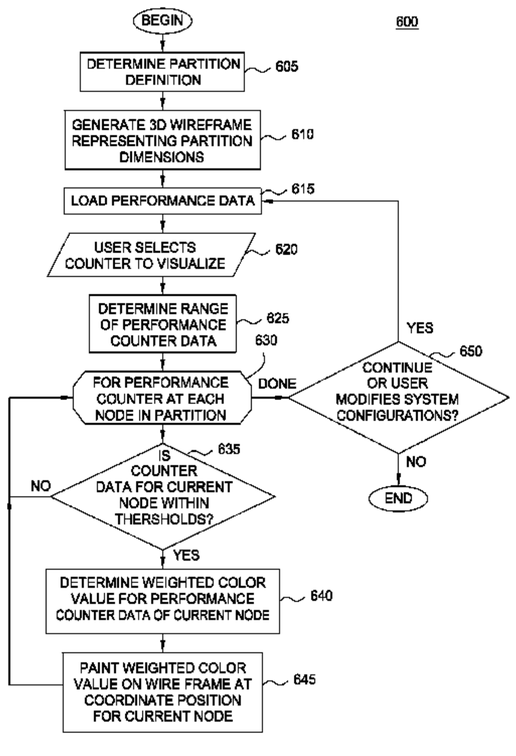
(57) **ABSTRACT**

An interactive tool is disclosed for visualizing performance data in real-time to enable adaptive performance optimization for an application running on a massively parallel computer system. The interactive tool may be used to visualize network congestion (and other) performance counters for an application as it runs on the parallel system in real-time. Further, a developer may use the interactive tool to experiment with various tuning options and optimization approaches on-the-fly.

19 Claims, 6 Drawing Sheets



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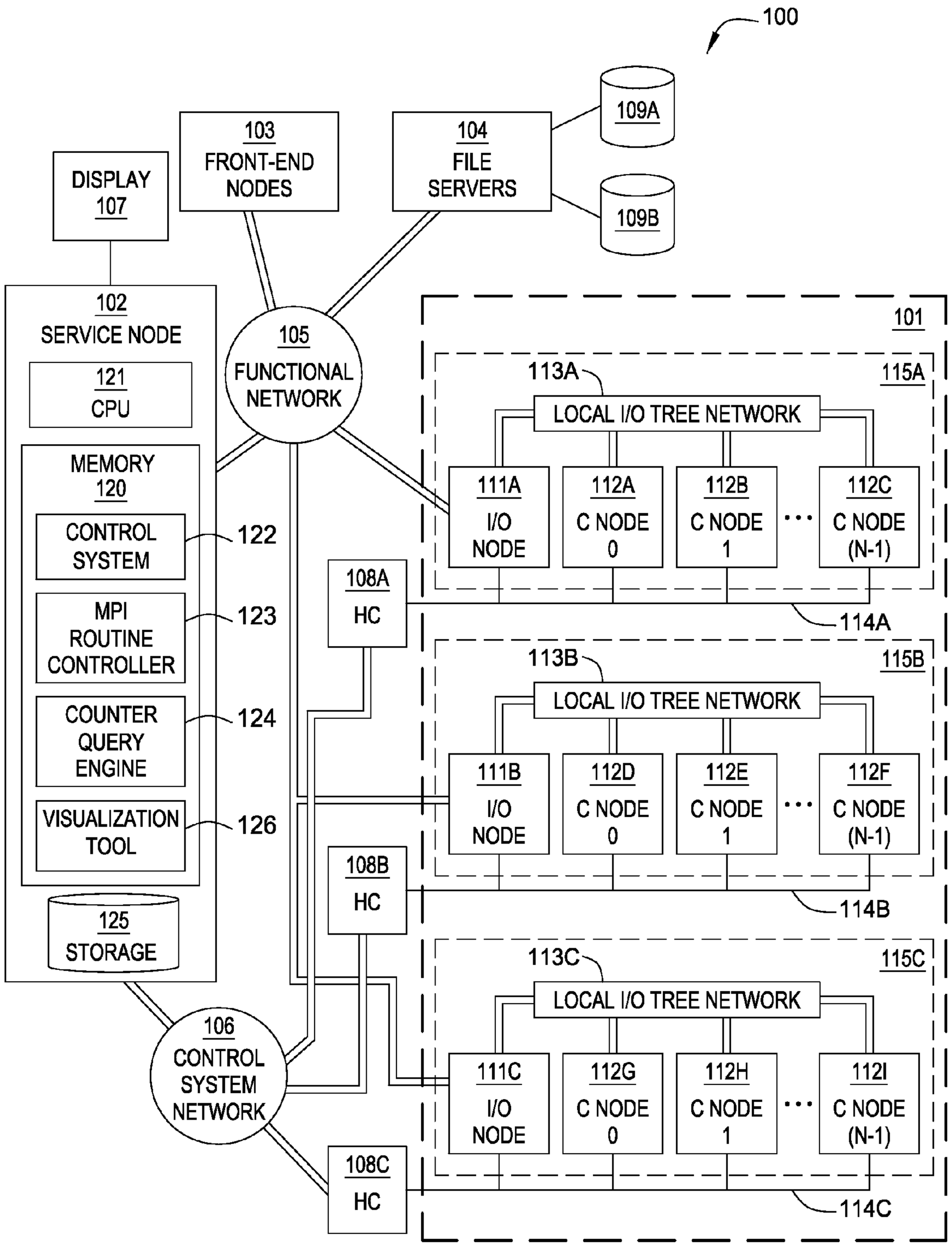
100
101
102
SERVICE NODE
121
CPU
MEMORY
120
CONTROL
SYSTEM
122
MPI
ROUTINE
CONTROLLER
123
COUNTER
QUERY
ENGINE
124
VISUALIZATION
TOOL
126
125
STORAGE
103
FRONT-END
NODES
104
FILE
SERVERS
109A
109B
105
FUNCTIONAL
NETWORK
106
CONTROL
SYSTEM
NETWORK
113A
LOCAL I/O TREE NETWORK
115A
111A
I/O
NODE
112A
C NODE
0
112B
C NODE
1
112C
C NODE
(N-1)
108A
HC
114A
113B
LOCAL I/O TREE NETWORK
115B
111B
I/O
NODE
112D
C NODE
0
112E
C NODE
1
112F
C NODE
(N-1)
108B
HC
114B
113C
LOCAL I/O TREE NETWORK
115C
111C
I/O
NODE
112G
C NODE
0
112H
C NODE
1
112I
C NODE
(N-1)
108C
HC
114C

FIG. 1

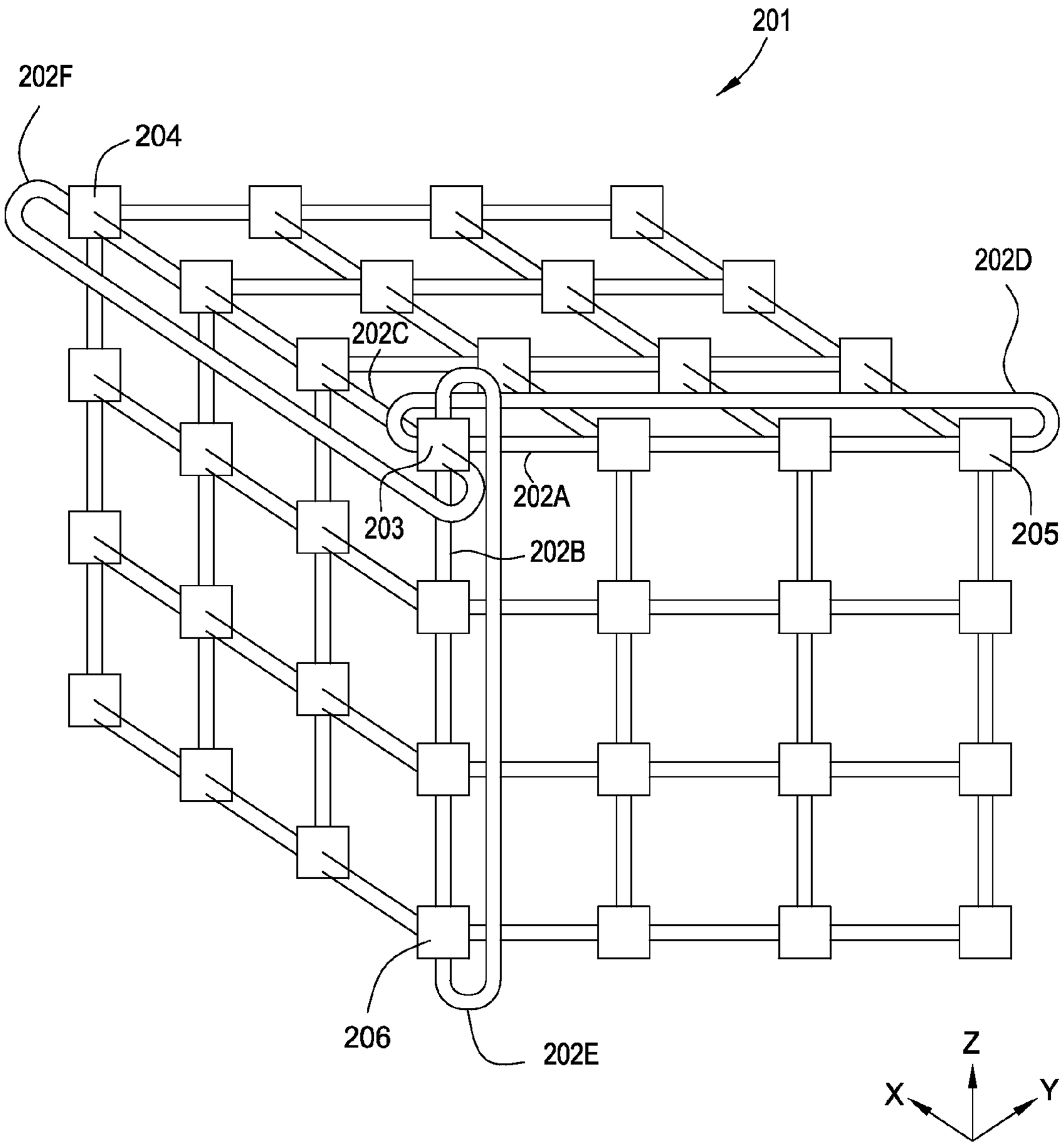

FIG. 2

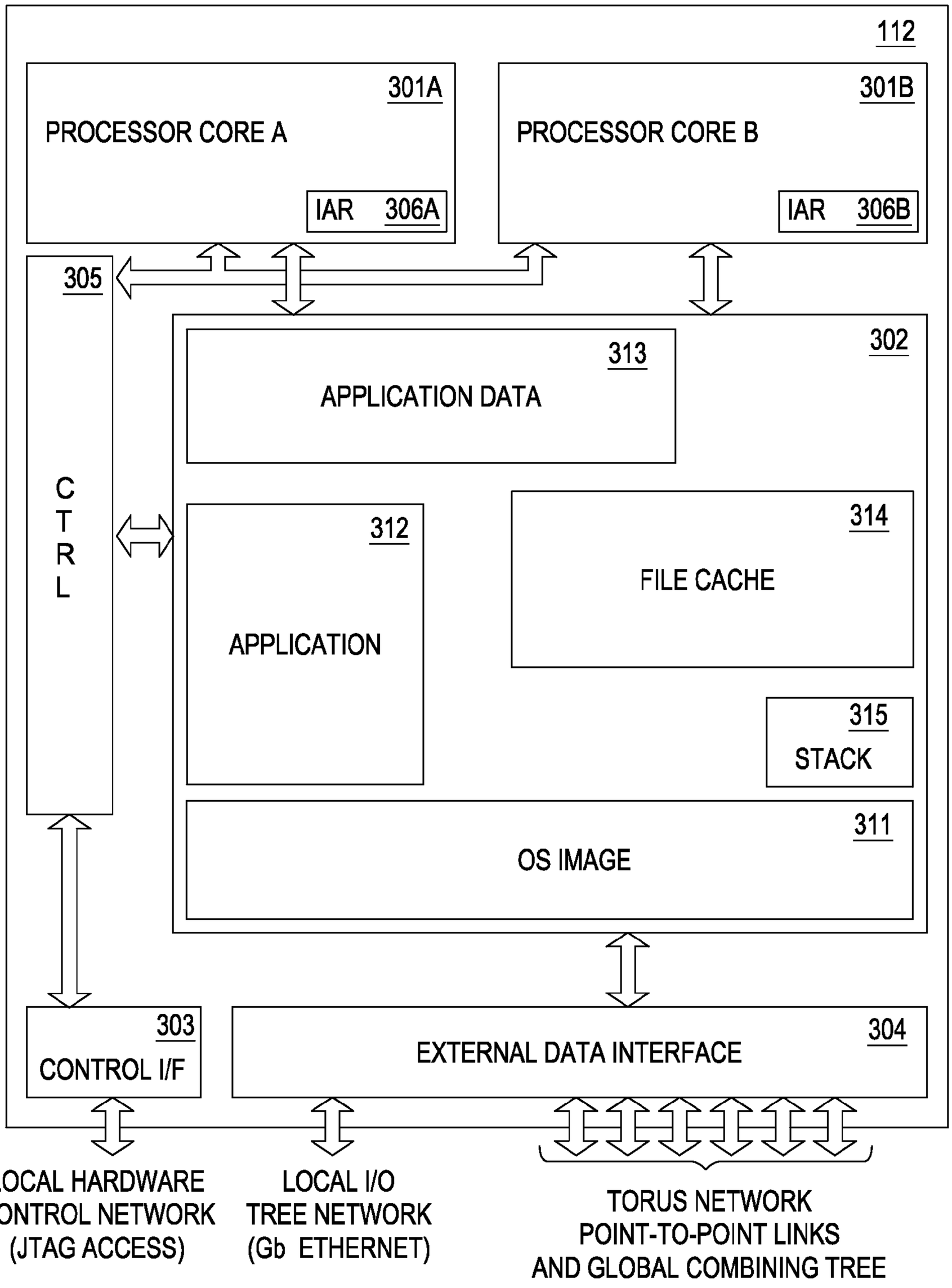
112
301A
PROCESSOR CORE A
IAR 306A
301B
PROCESSOR CORE B
IAR 306B
305
C T R L
302
313
APPLICATION DATA
312
APPLICATION
314
FILE CACHE
315
STACK
311
OS IMAGE
303
CONTROL I/F
304
EXTERNAL DATA INTERFACE
LOCAL HARDWARE CONTROL NETWORK (JTAG ACCESS)
LOCAL I/O TREE NETWORK (Gb ETHERNET)
TORUS NETWORK POINT-TO-POINT LINKS AND GLOBAL COMBINING TREE

FIG. 3

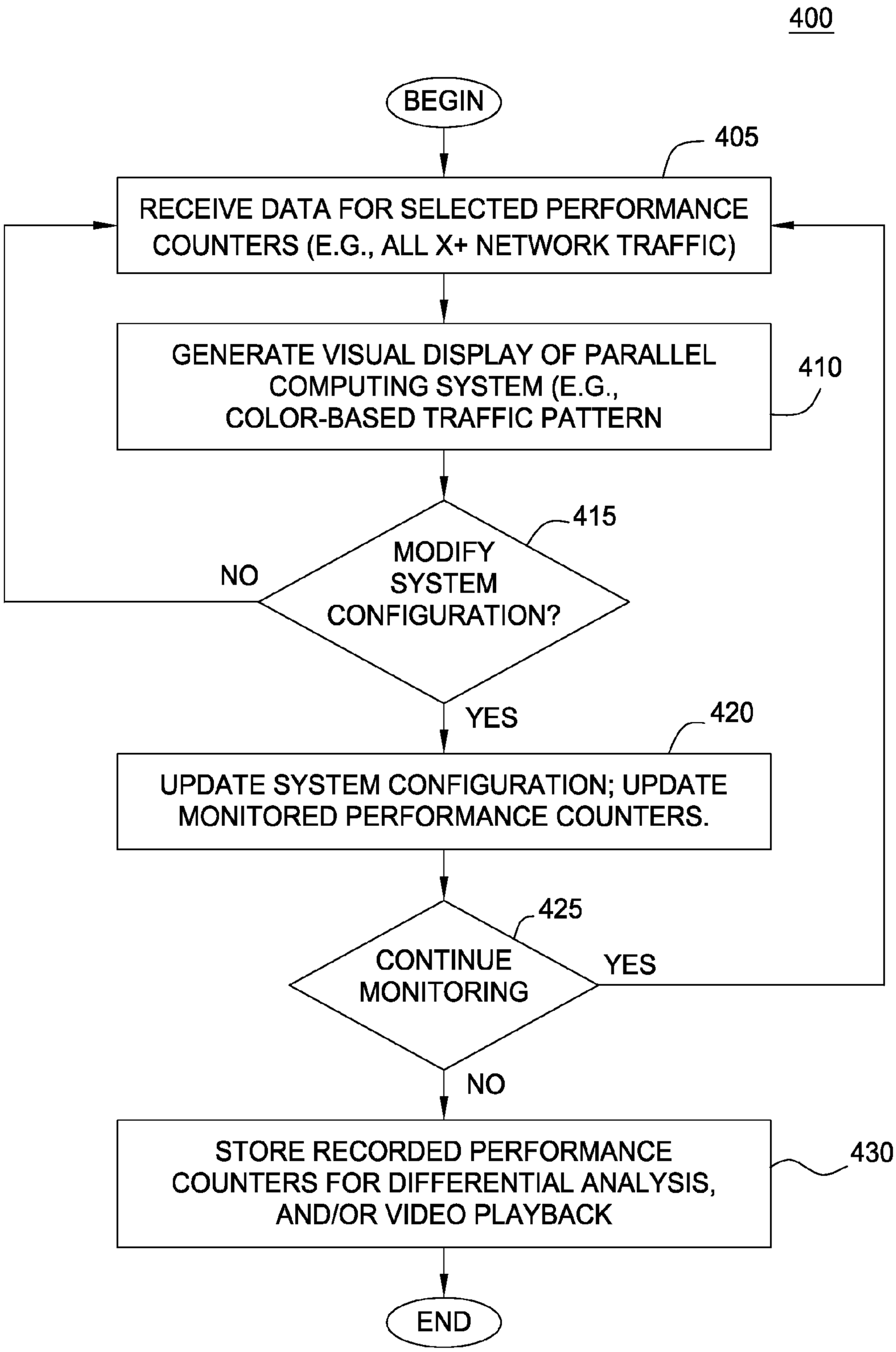
400
BEGIN
405
RECEIVE DATA FOR SELECTED PERFORMANCE COUNTERS (E.G., ALL X+ NETWORK TRAFFIC)
GENERATE VISUAL DISPLAY OF PARALLEL COMPUTING SYSTEM (E.G., COLOR-BASED TRAFFIC PATTERN
410
415
MODIFY SYSTEM CONFIGURATION?
NO
YES
420
UPDATE SYSTEM CONFIGURATION; UPDATE MONITORED PERFORMANCE COUNTERS.
425
CONTINUE MONITORING
YES
NO
STORE RECORDED PERFORMANCE COUNTERS FOR DIFFERENTIAL ANALYSIS, AND/OR VIDEO PLAYBACK
430
END

FIG. 4

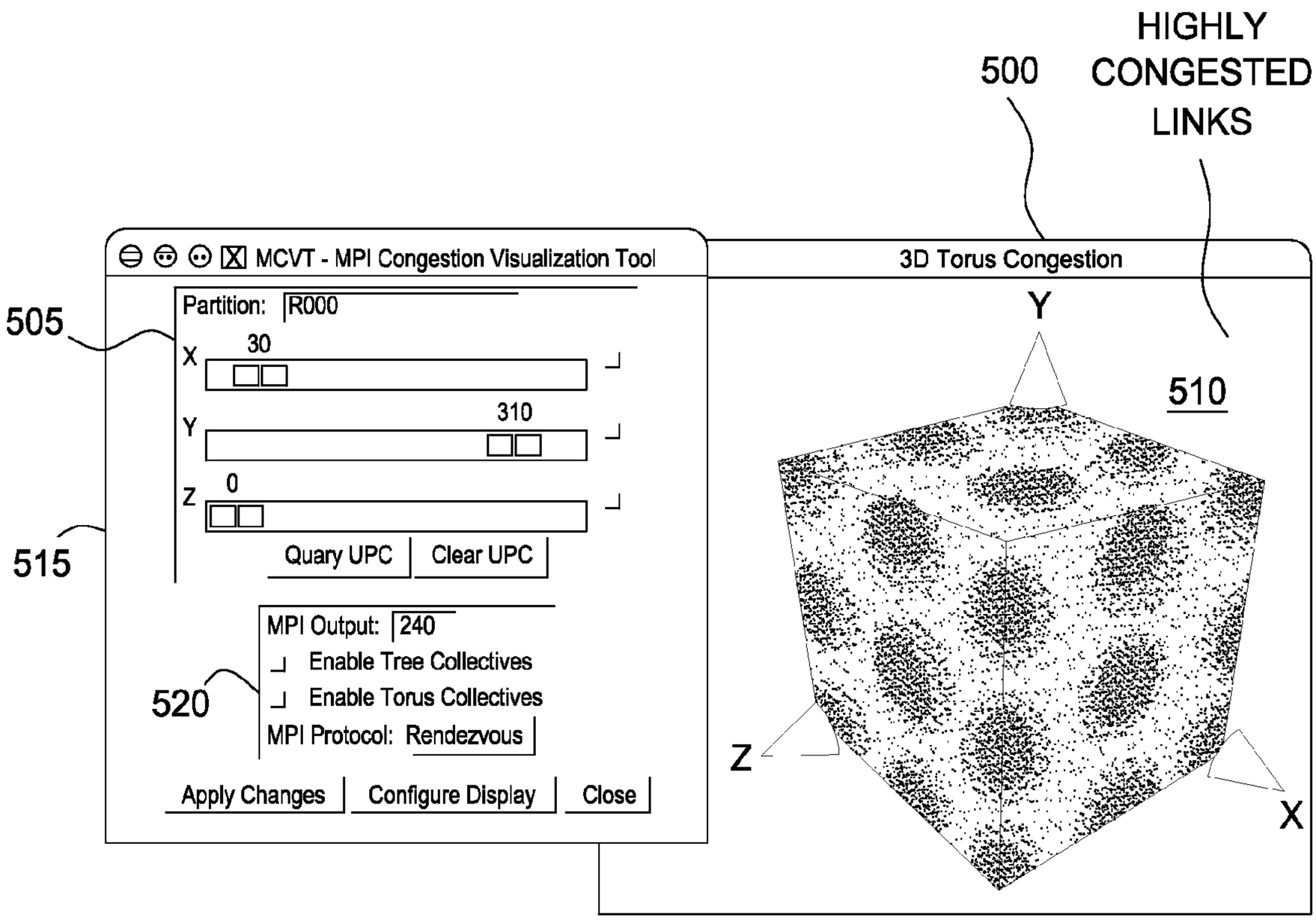
500
HIGHLY CONGESTED LINKS
MCVT - MPI Congestion Visualization Tool
3D Torus Congestion
505
Partition: R000
X 30
Y 310
Z 0
515
Quary UPC
Clear UPC
MPI Output: 240
Enable Tree Collectives
Enable Torus Collectives
520
MPI Protocol: Rendezvous
Apply Changes
Configure Display
Close
Y
510
Z
X

FIG. 5A

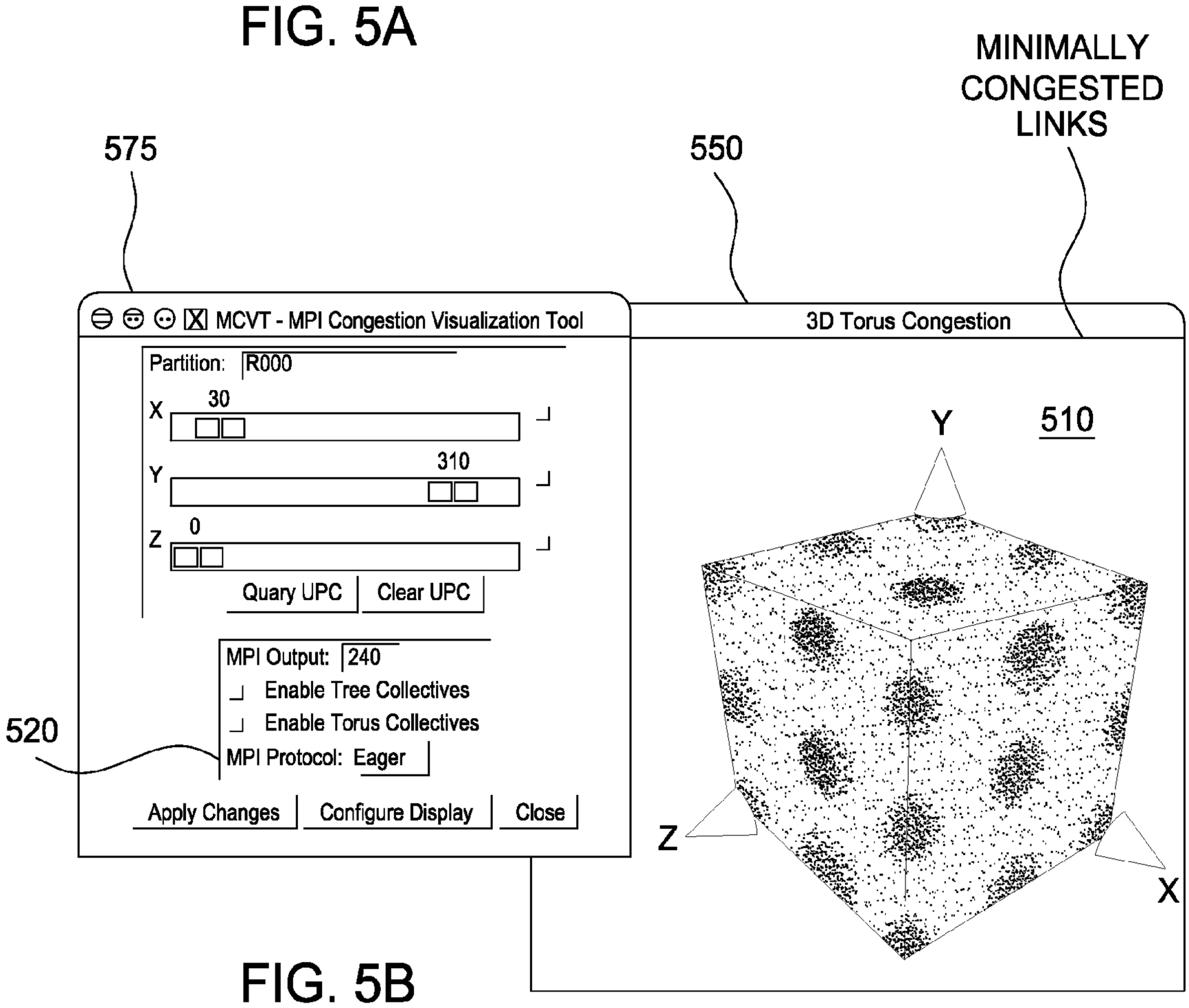
575
550
MINIMALLY CONGESTED LINKS
MCVT - MPI Congestion Visualization Tool
3D Torus Congestion
Partition: R000
X 30
Y 310
Z 0
Quary UPC
Clear UPC
MPI Output: 240
Enable Tree Collectives
Enable Torus Collectives
520
MPI Protocol: Eager
Apply Changes
Configure Display
Close
Y
510
Z
X

FIG. 5B

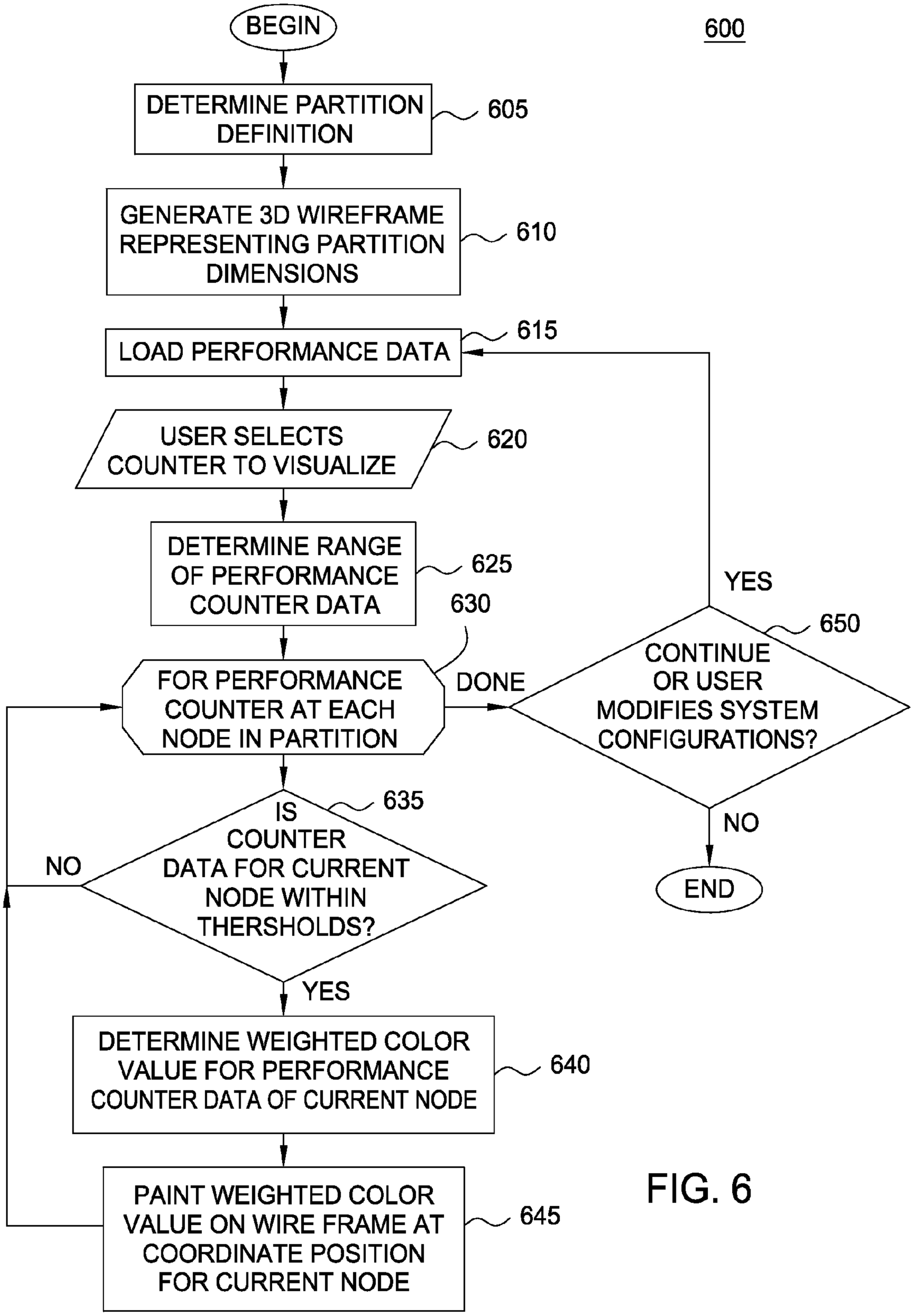
600
BEGIN
DETERMINE PARTITION DEFINITION
605
GENERATE 3D WIREFRAME REPRESENTING PARTITION DIMENSIONS
610
LOAD PERFORMANCE DATA
615
USER SELECTS COUNTER TO VISUALIZE
620
DETERMINE RANGE OF PERFORMANCE COUNTER DATA
625
630
FOR PERFORMANCE COUNTER AT EACH NODE IN PARTITION
DONE
CONTINUE OR USER MODIFIES SYSTEM CONFIGURATIONS?
650
YES
NO
END
IS COUNTER DATA FOR CURRENT NODE WITHIN THERSHOLDS?
635
NO
YES
DETERMINE WEIGHTED COLOR VALUE FOR PERFORMANCE COUNTER DATA OF CURRENT NODE
640
PAINT WEIGHTED COLOR VALUE ON WIRE FRAME AT COORDINATE POSITION FOR CURRENT NODE
645

FIG. 6

INTERACTIVE TOOL FOR VISUALIZING PERFORMANCE DATA IN REAL-TIME TO ENABLE ADAPTIVE PERFORMANCE OPTIMIZATION AND FEEDBACK

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to U.S. patent application Ser. No. 11/863,682, entitled "Interactive Tool for Visualizing Performance Data in Real-Time to Enable Adaptive Performance Optimization and Feedback", filed Sep. 28, 2007, by Gooding et al. This related patent application is herein incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to parallel computing. More specifically, the present invention relates to an interactive tool for visualizing performance data in real-time to enable adaptive performance optimization and feedback.

2. Description of the Related Art

Powerful computers may be designed as highly parallel systems where the processing activity of hundreds, if not thousands, of processors (CPUs) are coordinated to perform computing tasks. These systems are highly useful for a broad variety of applications including, financial modeling, hydrodynamics, quantum chemistry, astronomy, weather modeling and prediction, geological modeling, prime number factoring, image processing (e.g., CGI animations and rendering), to name but a few examples.

For example, one family of parallel computing systems has been (and continues to be) developed by International Business Machines (IBM) under the name Blue Gene®. The Blue Gene/L architecture provides a scalable, parallel computer that may be configured with a maximum of 65,536 (2^{16}) compute nodes. Each compute node includes a single application specific integrated circuit (ASIC) with 2 CPU's and memory. The Blue Gene/L architecture has been successful and on Oct. 27, 2005, IBM announced that a Blue Gene/L system had reached an operational speed of 280.6 teraflops (280.6 trillion floating-point operations per second), making it the fastest computer in the world at that time. Further, as of June 2005, Blue Gene/L installations at various sites worldwide were among five out of the ten top most powerful computers in the world.

In addition to the Blue Gene architecture developed by IBM, other highly parallel computer systems have been (and are being) developed. For example, a Beowulf cluster may be built from a collection of commodity off-the-shelf personal computers. In a Beowulf cluster, individual systems are connected using local area network technology (e.g., Gigabit Ethernet) and system software is used to execute programs written for parallel processing on the cluster of individual systems.

Compute nodes in a parallel system communicate with one another over one or more communication networks. For example, the compute nodes of a Blue Gene/L system are interconnected using five specialized networks, and the primary communication strategy for the Blue Gene/L system is message passing over a torus network (i.e., a set of point-to-point links between pairs of nodes). This message passing allows programs written for parallel processing to use high level interfaces such as Message Passing Interface (MPI) and Aggregate Remote Memory Copy Interface (ARMCI) to perform computing tasks and to distribute data among a set of

compute nodes. Other parallel architectures (e.g., a Beowulf cluster) also use MPI and ARMCI for data communication between compute nodes. Low level network interfaces communicate higher level messages using small messages known as packets. Typically, MPI messages are encapsulated in a set of packets which are transmitted from a source node to a destination node over a communications network (e.g., the torus network of a Blue Gene system).

Frequently, network contention is a major problem for the scalability of an application on a large parallel system. That is, compute nodes may compete with one another for access to the communication networks interconnecting the nodes on which the application is executing and as more compute nodes are dedicated to a given application, the more inter-node communication is typically required. Thus, it is desirable to optimize the configuration a given software application, including optimizing network communication patterns of the application. Further, communication patterns tend to be different at computational phases of program execution and are often quite complex.

Furthermore, supercomputing resources are a scarce commodity, and access to a parallel computing system is usually rented and/or allocated in small discrete blocks of time. When optimizing such an application, therefore, it is important to gather as much information on as many configurations of a parallel system and/or an application as is possible within an allotted time window.

Accordingly, there remains a need for an interactive tool for visualizing performance data in real-time to enable adaptive performance optimization and feedback on a large parallel computing system.

SUMMARY OF THE INVENTION

One embodiment of the invention provides a method a computer-implemented method of generating a visual representation of performance data for an application running on a plurality of compute nodes of a parallel computing system. The method generally includes receiving a selection of one or more performance counters present on the plurality of compute nodes and receiving a value for each of the selected performance counters. The values may be received without disrupting the performance of the application running on the plurality of compute nodes. The method also includes generating a visual display of the plurality of compute nodes that depicts the plurality of compute nodes and depicts a performance characteristic of the application, as reflected by the received values for each of the selected performance counters.

Another embodiment of the invention includes a computer-readable storage medium containing a program which, when executed, performs an operation of generating a visual representation of performance data for an application running on a plurality of compute nodes of a parallel computing system. The operation may generally include receiving a selection of one or more performance counters present on the plurality of compute nodes and receiving a value for each of the selected performance counters. The values may be received without disrupting the performance of the application running on the plurality of compute nodes. The operation may further include generating a visual display of the plurality of compute nodes that depicts the plurality of compute nodes and also depicts a performance characteristic of the application, as reflected by the received values for each of the selected performance counters.

Yet another embodiment of the invention provides a parallel computing system having a plurality of compute nodes

executing an application, each of the plurality of compute nodes having at least a processor and a memory. Each of the plurality of compute nodes may include one or more performance counters. The parallel system may also include a service node having at least a processor and a memory containing an interactive performance visualization tool. The visualization tool may be generally configured to receive a selection of one or more of the performance counters and receive a value for each of the selected performance counters. The values may be received without disrupting the performance of the application running on the plurality of compute nodes. The visualization too may be further configured to generate a visual display of the plurality of compute nodes, where the visual display depicts the plurality of compute nodes and also depicts a performance characteristic of the application, as reflected by the received values for each of the selected performance counters.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features, advantages and objects of the present invention are attained and can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof which are illustrated in the appended drawings.

It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. **1** is a high-level block diagram of components of a massively parallel computer system, according to one embodiment of the present invention.

FIG. **2** is a conceptual illustration of a three dimensional torus network of the system of FIG. **1**, according to one embodiment of the invention.

FIG. **3** is a high-level diagram of a compute node of the system of FIG. **1**, according to one embodiment of the invention.

FIG. **4** is a flow diagram illustrating a method for visualizing performance data in real-time to enable adaptive performance optimization and feedback on a massively parallel computer system, according to one embodiment of the invention.

FIGS. **5**A and **5**B illustrate an example user interface of an interactive tool for visualizing performance data in real-time to enable adaptive performance optimization and feedback, according to one embodiment of the invention.

FIG. **6** illustrates a method for generating a visualization of performance data in real-time, according to one embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the invention provide an interactive tool for visualizing performance data in real-time to enable adaptive performance optimization for an application running on a massively parallel computer system. For example, embodiments of the invention may be used to diagnose and alleviate network congestion problems and improve application scalability on message passing supercomputers such as the Blue Gene architecture developed by IBM. Of course, embodiments of the invention may be adapted for use with other parallel systems that use message passing for node-to-node communications. In one embodiment, an interactive tool may be used to visualize the network (and other) performance counters recorded for an application as the application runs on the parallel system in real-time. Further, a developer may use the interactive tool to experiment with various tuning options and optimization approaches on-the-fly.

The developer may use visual displays generated by the interactive tool to identify bottlenecks in the network communication patterns of an application as well as to devise improvements to those bottlenecks. Additionally, by displaying the network performance in real-time, the developer may immediately see the effect of a given change, allowing the developer to evaluate potential changes without having to repeatedly stop and start the application. This approach reduces the amount of time required to determine an optimal configuration for a given application.

In the following, reference is made to embodiments of the invention. However, it should be understood that the invention is not limited to specifically described embodiments. Instead, any combination of the following features and elements, whether related to different embodiments or not, is contemplated to implement and practice the invention. Furthermore, in various embodiments the invention provides numerous advantages over the prior art. However, although embodiments of the invention may achieve advantages over other possible solutions and/or over the prior art, whether or not a particular advantage is achieved by a given embodiment is not limiting of the invention. Thus, the following aspects, features, embodiments and advantages are merely illustrative and are not considered elements or limitations of the appended claims except where explicitly recited in a claim(s). Likewise, reference to "the invention" shall not be construed as a generalization of any inventive subject matter disclosed herein and shall not be considered to be an element or limitation of the appended claims except where explicitly recited in a claim(s).

One embodiment of the invention is implemented as a program product for use with a computer system. The program(s) of the program product defines functions of the embodiments (including the methods described herein) and can be contained on a variety of computer-readable media. Illustrative computer-readable media include, but are not limited to: (i) non-writable storage media (e.g., read-only memory devices within a computer such as CD-ROM or DVD-ROM disks readable by a CD- or DVD-ROM drive) on which information is permanently stored; (ii) writable storage media (e.g., floppy disks within a diskette drive, a hard-disk drive, volatile and non-volatile memory such as flash and dynamic random access memory) on which alterable information is stored. Other media include communications media through which information is conveyed to a computer, such as through a computer or telephone network, including wireless communications networks. The latter embodiment specifically includes transmitting information to/from the Internet and other networks. Such computer-readable media, when carrying computer-readable instructions that direct the functions of the present invention, represent embodiments of the present invention.

In general, the routines executed to implement the embodiments of the invention, may be part of an operating system or a specific application, component, program, module, object, or sequence of instructions. The computer program of the present invention typically is comprised of a multitude of instructions that will be translated by the native computer into a machine-readable format and hence executable instructions. Also, programs are comprised of variables and data structures that either reside locally to the program or are found in memory or on storage devices. In addition, various programs described hereinafter may be identified based upon

the application for which they are implemented in a specific embodiment of the invention. However, it should be appreciated that any particular program nomenclature that follows is used merely for convenience, and thus the invention should not be limited to use solely in any specific application identified and/or implied by such nomenclature.

FIG. **1** is a high-level block diagram of components of a massively parallel computer system **100**, according to one embodiment of the present invention. Illustratively, computer system **100** shows the high-level architecture of an IBM Blue Gene® computer system, it being understood that other parallel computer systems could be used, and the description of a preferred embodiment herein is not intended to limit the present invention.

As shown, computer system **100** includes a compute core **101** having a number of compute nodes arranged in a regular array or matrix, which perform the useful work performed by system **100**. The operation of computer system **100**, including compute core **101**, may be controlled by service node **102**. Various additional processors in front-end nodes **103** may perform auxiliary data processing functions, and file servers **104** provide an interface to data storage devices such as disk based storage **109**A, **109**B or other I/O (not shown). Functional network **105** provides the primary data communication path among compute core **101** and other system components. For example, data stored in storage devices attached to file servers **104** is loaded and stored to other system components through functional network **105**.

Also as shown, compute core **101** includes I/O nodes **111**A-C and compute nodes **112**A-I. Compute nodes **112** provide the processing capacity of parallel system **100** and are configured to execute applications written for parallel processing. I/O nodes **111** handle I/O operations on behalf of compute nodes **112**. Each I/O node **111** may include a processor and interface hardware that handles I/O operations for a set of N compute nodes **112**, the I/O node and its respective set of N compute nodes are referred to as a Pset. Compute core **101** contains M Psets **115**A-C, each including a single I/O node **111** and N compute nodes **112**, for a total of M×N compute nodes **112**. The product M×N can be very large. For example, in one implementation M=1024 (1K) and N=64, for a total of 64K compute nodes.

In general, application programming code and other data input required by compute core **101** to execute user applications, as well as data output produced by the compute core **101**, is communicated over functional network **105**. The compute nodes within a Pset **115** communicate with the corresponding I/O node over a corresponding local I/O tree network **113**A-C. The I/O nodes, in turn, are connected to functional network **105**, over which they communicate with I/O devices attached to file servers **104**, or with other system components. Thus, the local I/O tree networks **113** may be viewed logically as extensions of functional network **105**, and like functional network **105** are used for data I/O, although they are physically separated from functional network **105**.

In a Blue Gene system, compute nodes **112** are connected by multiple independent networks. Other massively parallel architectures also use multiple networks for node-to-node communication. Specifically, in a Blue Gene system, a torus network connects the compute nodes **112** in a 3D mesh with wrap around links. Each compute node **112** is connected to its six neighbors through the torus network, and is addressed by an (x, y, z) coordinate in within the mesh. Thus, each compute node **112** may transmit a message directly to a neighboring node in the X+ and X−, the Y+ and Y−, and the Z+ and Z− directions.

FIG. **2** is a conceptual illustration of a three-dimensional torus network of system **100**, according to one embodiment of the invention. More specifically, FIG. **2** illustrates a 4×4×4 torus **201** of compute nodes, in which the interior nodes are omitted for clarity. Although FIG. **2** shows a 4×4×4 torus having 64 nodes, it will be understood that the actual number of compute nodes in a parallel computing system is typically much larger. For example, a complete Blue Gene/L system includes 65,536 compute nodes. Each compute node **112** in torus **201** includes a set of six node-to-node communication links **202**A-F which allows each compute nodes in torus **201** to communicate with its six immediate neighbors, two nodes in each of the x, y and z coordinate dimensions.

As used herein, the term "torus" includes any regular pattern of nodes and inter-nodal data communications paths in more than one dimension, such that each node has a defined set of neighbors, and for any given node, it is possible to determine the set of neighbors of that node. A "neighbor" of a given node is any node which is linked to the given node by a direct inter-nodal data communications path. That is, a path which does not have to traverse another node. The compute nodes may be linked in a three-dimensional torus **201**, as shown in FIG. **2**, but may also be configured to have more or fewer dimensions. Also, it is not necessarily the case that a given node's neighbors are the physically closest nodes to the given node, although it is generally desirable to arrange the nodes in such a manner, insofar as possible.

The compute nodes in each of the x, y, or z dimensions form a torus in that dimension because the point-to-point communication links logically wrap around. As shown, for example, links **202**D, **202**E, and **202**F which wrap around from compute node **203** to other end of compute core **201** in each of the x, y and z dimensions. Thus, although node **203** appears to be at a "corner" of the torus, node-to-node links **202**A-F link node **203** to nodes **204**, **205**, and **206**, in the x, y, and Z dimensions of torus **201**.

Referring again to FIG. **1**, another network on the Blue Gene system is a global combining network (i.e., tree network **113**), which connects compute nodes **112** in a binary tree. In the combining network, each compute node **112** has a parent and two children (although some nodes may have zero or one child, depending on the hardware configuration). It is also important to note that in the Blue Gene architecture, the tree and torus networks are independent networks. That is, these networks do not share network resources such as links or packet injection FIFOs. Communication networks in other parallel architectures have similar characteristics.

A third network on a Blue Gene system is the JTAG (Joint Test Action Group) network (i.e., control system network **106**), which may be configured to provide a hardware monitoring facility. As is known, JTAG is a standard for providing external test access to integrated circuits serially, via a four- or five-pin external interface. The JTAG standard has been adopted as an IEEE standard. Within the Blue Gene system, the JTAG network may be used to send performance counter data to service node **102** in real-time. That is, while an application is running on compute core **101**, performance data may be gathered and transmitted to service node **102** without affecting the performance of that application. For example, in one embodiment, the JTAG network may be used to record floating point and cache performance on a given compute node **112**, along with the number of network packets that pass through any of the six network ports (X+, X−, Y+, Y−, Z+, Z−) on that compute node **112**. These hardware counters allow the network traffic (and memory access performance) to be monitored without affecting the performance of the application being monitored. Further, in one embodiment, the JTAG net-

work may be used to modify the operational state of compute core **101** while an application is running, without disrupting application performance. For example, the JTAG network may be used to specify what message passing protocol should be used by compute nodes **112** (or to adjust a configuration for a current message passing protocols).

Service node **102** communicates control and state information with the nodes of compute core **101** over control system network **106**. Network **106** is coupled to a set of hardware controllers **108**A-C (e.g., a JTAG controller). Each hardware controller communicates with the nodes of a respective Pset **115** over a corresponding local hardware control network **114**A-C. The hardware controllers **108** and local hardware control networks **114** are logically an extension of control system network **106**, although physically separate.

In one embodiment, service node **102** may be configured to direct and/or monitor the operation of the compute nodes **112** in compute core **101**. Service node **102** is a computer that includes a processor (or processors) **121**, internal memory **120**, and local storage **125**. A display device **107** provides an LCD or CRT display monitor. Illustratively, memory **120** of service node **102** includes a control system **122**, an MPI runtime controller **123**, a performance counter query tool **124**, and a visualization tool **126**.

Control system **122** may be a software application configured to control the allocation of compute nodes **112** in compute core **101**, direct the loading of application and data on compute nodes **111**, and perform diagnostic and maintenance functions, among other things. MPI runtime controller **124** may be a software application used to configure the protocols used by compute nodes **111** to communicate using MPI (or other) messages. For example, MPI runtime controller **124** may be used to select between message passing strategies such as the well-known "eager" and "rendezvous" protocols. When using the eager protocol, a sending node assumes that a receiving node can receive and store the message if it is sent. The receiving node has the responsibility to buffer the message upon its arrival. The eager protocol is generally used for smaller message sizes (typically up to Kbytes in size). The rendezvous protocol is used when assumptions about the receiving process buffer space cannot be made, or when a message size limit specified for the eager protocol is exceeded. The rendezvous protocol requires some type of "handshaking" between the sender and the receiver processes. Typically, in a rendezvous implementation, the sender must first send a request and receive an acknowledgment before a message may be transferred.

In one embodiment, performance counter query tool **124** may be a software application configured to query and report on performance counter data received over control system network **106**. For example, query tool **124** may collect the counter values representing the number of network packets that pass through any of the six network ports (X+, X−, Y+, Y−, Z+, Z−) on a given compute node **112**. Visualization tool **126** may be a software application configured to use the performance counter data received from query tool **124** and generate a visual representation of the performance of parallel computing system **100**. For example, the visualization tool **126** may be configured to alter the colors used to depict a compute node as the counter value increases. In such a case, the color may depend on the traffic that passes through a single network port (e.g., X+) or may be a composite of all traffic through a given node. To provide a visual display reflecting network contention, compute nodes **112** in a state of high contention may be displayed more red than compute nodes **112** in a state of low contention. Further, in one embodiment, visualization tool **126** may also provide a variety of visualization techniques which could be employed by the developer (e.g., a display of a selected slice of the compute nodes or a fly-through animation, etc.).

In addition to service node **102**, front-end nodes **103** provide computer systems used to perform auxiliary functions which, for efficiency or otherwise, are best performed outside compute core **101**. Functions which involve substantial I/O operations are generally performed in the front-end nodes. For example, interactive data input, application code editing, or other user interface functions are generally handled by front-end nodes **103**, as is application code compilation. Front-end nodes **103** are connected to functional network **105** and may communicate with file servers **104**.

FIG. **3** is a high-level diagram of a compute node **112** of the system **100** of FIG. **1**, according to one embodiment of the invention. As shown, compute node **112** includes processor cores **301**A and **301**B, and also includes memory **302** used by both processor cores **301**; an external control interface **303** which is coupled to local hardware control network **114**; an external data communications interface **304** which is coupled to the corresponding local I/O tree network **113**, and the corresponding six node-to-node links **202** of the torus network **201**; and monitoring and control logic **305** which receives and responds to control commands received through external control interface **303**. Monitoring and control logic **305** may access processor cores **301** and locations in memory **302** on behalf of service node **102** to read (or in some cases alter) the operational state of node **112**. In one embodiment, each node **112** may be physically implemented as a single, discrete integrated circuit chip.

As described, functional network **105** may service many I/O nodes, and each I/O node is shared by multiple compute nodes **112**. Thus, it is apparent that the I/O resources of parallel system **100** are relatively sparse when compared to computing resources. Although it is a general purpose computing machine, parallel system **100** is designed for maximum efficiency in applications which are computationally intense.

As shown in FIG. **3**, memory **302** stores an operating system image **311**, an application code image **312**, and user application data structures **313** as required. Some portion of memory **302** may be allocated as a file cache **314**, i.e., a cache of data read from or to be written to an I/O file. Operating system image **311** provides a copy of a simplified-function operating system running on compute node **112**. Operating system image **311** may includes a minimal set of functions required to support operation of the compute node **112**. In a Blue Gene system, for example, operating system image **311** contains a version of the Linux® operating system customized to run on compute node **112**. Of course, other operating systems may be used, and further it is not necessary that all nodes employ the same operating system. (Also note, Linux® is a registered trademark of Linus Torvalds in the United States and other countries.)

Application code image **312** represents a copy of the application code being executed by compute node **112**. Application code image **302** may include a copy of a computer program being executed by system **100**. In one embodiment, each node may execute an identical copy of the same application, where each copy is configured to cooperate with others. Alternatively, an application may be configured as a collection of dissimilar components configured to perform specialized tasks as part of the parallel application processing. Memory **302** may also include a call-return stack **315** for storing the states of procedures which must be returned to,

which is shown separate from application code image **302**, although it may be considered part of application code state data.

As part of ongoing operations, application **312** may be configured to transmit packets from compute node **112** to other compute nodes in parallel system **100**. For example, the high level MPI call of MPI_Send( ); may be used by application **312** to transmit a message (encapsulated in a sequence of packets) from one compute node to another. On the other side of the communication, the receiving node may invoke the MPI call MPI_Receive( ); to receive and process the message. As described above, in one embodiment, each compute node **112** may include hardware based counters configured to count now many packets are passed over the external data interface **304** of a given compute node **112** and report this information to service node **102** over control system network **106** using control network interface **303**.

FIG. **4** is a flow diagram illustrating a method for visualizing performance data in real-time to enable adaptive performance optimization and feedback on a massively parallel computer system, according to one embodiment of the invention. As shown, the method **400** begins at step **405**, where data for a selected performance counter is received. For example, as stated, the performance counters may record the number of messages that pass through a given network port (e.g. X+) of each compute node **112** running a given application.

At step **410**, a visual display is generated that shows the performance of the parallel system. The visual display depicts the performance counter data received at step **405**. For example, the visual representation may depict network congestion on the 3-D torus of a Blue Gene system. Doing so may allow application developers and other users to detect "hotspots" (i.e., areas of significant network congestion), patterns of usage and potential inefficiency, etc. In one embodiment, the visual display may be generated and displayed in real-time. That is, it may be generated and displayed while the application is actively executing on the compute nodes of the parallel system. Further, the visual display may be updated in real-time to reflect the ongoing performance of the application running on the parallel computing system as different functions are performed.

By reviewing the visual display, the developer may formulate possible changes to the configuration of the parallel system to increase the performance and scalability of the application. At step **415**, the visualization tool **126** determines whether the system configuration has been modified. If not, then the method returns to step **405** and continues to update the visual representation of application performance on the parallel system.

Otherwise, at step **420**, the parallel system configuration and/or the monitored performance counters may be updated. For example, the developer may experiment with application performance in real-time by trying different routing protocols or by modifying the values of network communication parameters. In such a case, the developer could switch the routing protocol from eager to rendezvous (or vice versa), or could explore alternative routing schemes (e.g., transporter nodes, implicit barrier remapping, alternative static routing heuristics, etc.), adjust MPI environment variables, and other experiments to evaluate how network performance (and thus application scaling) is affected in real-time. In one embodiment, service node **102** may communicate changes to the configuration of the parallel system using control system **106** (e.g., via the JTAG network of a Blue Gene system). Depending on the particular change, the change could take affect immediately (e.g., a hardware configuration change). In other cases, the change could take affect at the next stage of the application (e.g., if MPI messages are needed to change protocols at a defined state or change which performance counters are monitored).

At step **425**, if the developer wishes to continue monitoring, then the method **400** returns to step **405**. Otherwise, at step **430**, data recorded from a given session may be stored. For example, the performance counter data may be stored for later differential analysis and/or a time-lapse payback. That is, visualization tool may be configured to display the differences between two performance measurements. In such a case, the visualization tool may be used generate a display by subtracting the performance counter data before and after a change was made to the network routing. This would allow the performance changes caused by an experiment to be highlighted. For example, the difference between executing an application on the compute nodes of a parallel system using the eager protocol versus the rendezvous protocol could be displayed.

Further, in one embodiment, the visualization tool may facilitate an analysis of the communication patterns of an application over time. Storing the performance counter data allows it to be used to generate a time-lapse animation sequence of application performance. The developer may use an interface provided by visualization tool **126** to rewind back to previously viewed performance data, pause to study a certain instance of network contention, fast forward at a user selected speed (½ times (X) faster, 1×, 2×, 3×, etc.), skip forward or backward to certain phases, etc.

FIGS. **5**A and **5**B illustrate an example user interface of an interactive tool for visualizing performance data in real-time to enable adaptive performance optimization and feedback, according to one embodiment of the invention. As shown in FIG. **5**A, visual display **500** depicts a representation of an application's network communication pattern projected onto the compute nodes of a three-dimensional torus network **510** (e.g., a torus network of a Blue Gene system). Illustratively, the torus network **510** illustrated in visual display **500** has a high degree of network congestion on the node-to-node communication links, represented by the dense level of darkly shaded regions of torus network **510**. Also, a dialog box **515** includes a node selection tool **505** used to specify and query for the performance data related to a given compute node **112**. Dialog box **515** also includes an MPI configuration tool **520**. In this example, MPI configuration tool **520** has been used to set MPI communications on the torus network to use the rendezvous protocol.

FIG. **5**B shows a visual display **550** after reconfiguring the application running on torus network **510** to use the eager protocol for MPI message passing. MPI configuration tool **520** of dialog box **575** now shows that the eager protocol has been selected. In this example, assume that using eager protocol leads to substantially less network congestion for the application running on the torus network **510**. Accordingly, the relative level of congestion shown on the torus network **510** shown in visual display **550** depicts minimally congested links, relative to the amount of network congestion in visual display **500**, illustrating the reduction in network contention that resulted from the change from the rendezvous protocol to the eager protocol.

FIG. **6** illustrates a method **600** for generating a visualization of performance data in real-time, such as the visualization of torus **510** shown in FIGS. **5**A and **5**B, according to one embodiment of the invention. The method **600** begins at step **605** where visualization tool **126** may determine an active partition currently running an application. For example, on a Blue Gene system, applications run on a block of partitions composed from compute nodes in an x, y, and z dimension.

When the dimensions are the same (i.e., when x=y=z), the partition forms the shape of a cube, such as the torus **510** shown in FIG. **5**A.

At step **610**, the visualization tool **126** may generate a 3D wireframe representing the partition dimensions. And at step **615**, the visualization tool **126** may load performance data related to the application being run on the parallel system. As described above, in one embodiment, the performance data may be collected through a JTAG network independently from the actions of the application. That is, the performance data may be collected without having an impact on the performance of the running application. At step **620**, a user may select which performance counters the user would like to visualize. For example, as described, performance counters may record the number of network packets injected on each of the six point-to-point links from each compute node in the partition running the application. Other performance counters include the number of floating point multiply operations performed at each compute node, or memory utilization counters, e.g., the number of cache misses/hits or the number of DDR paging operations, performed at each compute node.

At step **625**, the visualization tool **126** may determine a minimum and maximum value for the performance counter selected at step **620**. In one embodiment, the range between the maximum and minimum value is used to determine a weighted color value for the performance counter for each node. For example, if the performance data for network traffic ranged from 0 to 200 packets per node, this information could be visualized by assigning different color values to different ranges of packets. Thus, the color values assigned to the busiest node (e.g., nodes in the top 10% with 180-200 packets) could be painted on the wireframe in red. In contrast, color values assigned to the least busy node (e.g., nodes in the bottom 10% with 0-20 packets) could be painted on the wireframe in blue. Further, in one embodiment, thresholds may be set to prevent intermittent traffic from cluttering the visual display. For example, a threshold may require that a node exhibit a minimum amount of network traffic before being shown on the visualization.

Once the user has specified what performance data to be visualized, and the visualization tool **126** has retrieved this data, at step **630** a loop begins to generate a visual display showing the performance of the application running on the partition, relative to the performance counter selected at step **620**. At step **635**, the visualization tool **126** determines whether the counter data for a current node is within any minimum or maximum thresholds specified by the user. If not, then tool returns to step **630** and evaluates the performance counter data for another node. Otherwise, at step **640**, visualization tool **126** calculates a weighed color value for the current node, based on the range of values for the selected performance counter and the value of the performance counter for the current node. At step **645**, the color value determined at step **640** is used to color a portion of the 3D wireframe generated at step **610**. In particular, a position corresponding to the coordinate position of the current node within the partition.

In one embodiment, the process of loading performance data (step **615**) and the loop of steps **630**, **635**, **640**, and **645**, may continue until the user decides either to quit or to modify the system configuration at step **650**. Thus, the visualization may take on the appearance of an animation showing "hot" regions of the application running on the partition as the performance characteristics of the application change over time.

Advantageously, embodiments of the invention may be used to increase the performance and scalability of an application running on a massively parallel computing system, such as a Blue Gene system. The performance visualization tool disclosed herein may be used to visualize the network (and other) performance counters of the parallel system during application execution in real-time. Further, a developer may experiment with various tuning options and optimization approaches on-the-fly. The ability to visualize the network performance of an application as it executes allows the developer to identify bottlenecks in the network communication patterns of the application and thus devise improvements to those bottlenecks. Moreover, by displaying the network performance in real-time, the developer may immediately see the effect of a given change, allowing the developer to evaluate potential changes without having to repeatedly stop and start the application.

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A non-transitory computer-readable medium containing a program which, when executed, performs an operation of generating a visual representation of performance data for an application running on a plurality of compute nodes of a parallel computing system, wherein instances of the application communicate with one another using a first network, the operation comprising:

receiving a value for each of one or more dedicated hardware performance counters present on the plurality of compute nodes, wherein the values are received without disrupting the performance of the application running on the plurality of compute nodes by using a second network that is separate from the first network, and wherein at least one of the dedicated hardware performance counters is configured to count a number of packets that pass through a plurality of network ports coupled to one of the plurality of compute nodes;

determining a maximum value for each of the dedicated hardware performance counters and a minimum value for each of the dedicated hardware performance counters, wherein the maximum value represents the maximum value for the dedicated hardware performance counter across all of the plurality of compute nodes, and wherein the minimum value represents the minimum value for the dedicated hardware performance counter across all of the plurality of compute nodes;

for each of the plurality of compute nodes, determining a weighted color value relative to the received values for the other compute nodes in the plurality of compute nodes, wherein the weighted color value is based on the received value for each respective compute node, the respective maximum value for the performance counter, and the respective minimum value for the performance counter; and

generating a three-dimensional visual display representing the plurality of compute nodes, wherein the three-dimensional visual display depicts a network topology of the plurality of compute nodes, and wherein the three-dimensional visual display is colored based on the weighted color value determined for each of the plurality of compute nodes.

2. The non-transitory computer-readable medium of claim **1**, wherein the communication links interconnect the plurality of compute nodes as a multi-dimensional torus.

3. The non-transitory computer-readable medium claim 1, wherein the plurality of compute nodes pass messages using the Message Passing Interface (MPI) protocol.

4. The non-transitory computer-readable medium of claim 1, wherein a second one of the dedicated hardware performance counters measures one of a floating point performance and a cache performance on a given compute node of the plurality of compute nodes.

5. The non-transitory computer-readable medium of claim 1, wherein the operation further comprises:

modifying a configuration setting of the plurality of compute nodes of the parallel computing system, wherein the configuration setting may be modified without disrupting the application running on the plurality of compute nodes; and

receiving an updated value for each of the dedicated hardware performance counters, wherein the updated values are received without disrupting the performance of the application running on the plurality of compute nodes by using a dedicated, second network that is separate from the first network; and

generating an updated three-dimensional visual display representing the plurality of compute nodes, wherein the updated three-dimensional visual display depicts the network topology of the plurality of compute nodes, and wherein the updated three-dimensional visual display is colored based on an updated weighted color value determined for each of the plurality of compute nodes, based on the received updates value for each of the plurality of compute nodes.

6. The non-transitory computer-readable medium of claim 5, wherein the operation further comprises storing the generated three-dimensional visual display and the updated three-dimensional visual display.

7. The non-transitory computer-readable medium of claim 1, wherein the operation further comprises, generating a time-lapse animation depicting changes in the dedicated hardware performance counters that occur while the application is running on the parallel system.

8. A parallel computing system, comprising:

a plurality of compute nodes executing an application, each of the plurality of compute nodes having at least a processor and a memory, wherein each of the plurality of compute nodes includes one or more dedicated hardware performance counters, and wherein instances of the application communicate with one another using a first network; and

a service node having at least a processor and a memory containing an interactive performance visualization tool, wherein the visualization tool is configured to:

receive a value for each of the one or more dedicated hardware performance counters, wherein the values are received without disrupting the performance of the application running on the plurality of compute nodes, by using a second network that is separate from the first network, and wherein at least one of the dedicated hardware performance counters is configured to count a number of packets that pass through a plurality of network ports coupled to one of the plurality of compute nodes,

determine a maximum value for each of the dedicated hardware performance counters and a minimum value for each of the dedicated hardware performance counters, wherein the maximum value represents the maximum value for the dedicated hardware performance counter across all of the plurality of compute nodes, and wherein the minimum value represents the minimum value for the dedicated hardware performance counter across all of the plurality of compute nodes;

for each of the plurality of compute nodes, determine a weighted color value relative to the received values for the other compute nodes in the plurality of compute nodes, wherein the weighted color value is based on the received value for each respective compute node, the respective maximum value for the performance counter, and the respective minimum value for the performance counter; and

generate a three-dimensional visual display representing the plurality of compute nodes, wherein the three-dimensional visual display depicts a network topology of the plurality of compute nodes, and wherein the three-dimensional visual display is colored based on the weighted color value determined for each of the plurality of compute nodes.

9. The parallel computing system of claim 8, wherein the communication links interconnect the plurality of compute nodes as a multi-dimensional torus.

10. The parallel computing system claim 8, wherein the plurality of compute nodes pass messages using the Message Passing Interface (MPI) protocol.

11. The parallel computing system of claim 8, wherein a second one of the one or more performance counters measures one of a floating point performance and a cache performance on a given compute node of the plurality of compute nodes.

12. The parallel computing system of claim 8, wherein the visualization tool is further configured to:

modify a configuration setting of the plurality of compute nodes of the parallel computing system, wherein the configuration setting may be modified without disrupting the application running on the plurality of compute nodes;

receive an updated value for each of the dedicated hardware performance counters, wherein the updated values are received without disrupting the performance of the application running on the plurality of compute nodes by using a dedicated, second network that is separate from the first network; and

generate an updated three-dimensional visual display representing the plurality of compute nodes, wherein the updated three-dimensional visual display depicts the network topology of the plurality of compute nodes, and wherein the updated three-dimensional visual display is colored based on an updated weighted color value determined for each of the plurality of compute nodes, based on the received updates value for each of the plurality of compute nodes.

13. The parallel computing system of claim 12, wherein the visualization tool is further configured to store the generated three-dimensional visual display and the updated three-dimensional visual display.

14. The parallel computing system of claim 13, wherein the visualization tool is further configured to generate a time-lapse animation depicting changes in the dedicated hardware performance counters that occur while the application is running on the parallel system.

15. A non-transitory computer-readable medium containing a program which, when executed, performs an operation of generating a visual representation of performance data for an application running on a plurality of compute nodes of a parallel computing system, wherein instances of the application communicate with one another using a first network, the operation comprising:

receiving a value for each of one or more dedicated hardware performance counters present on the plurality of compute nodes, wherein the values are received without disrupting the performance of the application running on the plurality of compute nodes by using a second network that is separate from the first network, and wherein at least one of the dedicated hardware performance counters is configured to count a number of packets that pass through a plurality of network ports coupled to one of the plurality of compute nodes;

modifying a configuration setting of the plurality of compute nodes of the parallel computing system, wherein the configuration setting may be modified without disrupting the application running on the plurality of compute nodes;

receiving an updated value for each of the dedicated hardware performance counters, wherein the updated values are received without disrupting the performance of the application running on the plurality of compute nodes, by using the second network;

calculating a difference between the received value and the received updated values for each of the plurality of compute nodes for each of the one or more dedicated hardware performance counters;

determining a maximum difference value for the dedicated hardware performance counter and a minimum difference value for the dedicated hardware performance counter, wherein the maximum difference value represents the maximum value of the calculated difference for the dedicated hardware performance counter across all of the plurality of compute nodes, and wherein the minimum difference value represents the minimum value of the calculated difference for the dedicated hardware performance counter across all of the plurality of compute nodes;

for each of the plurality of compute nodes, determining a weighted color value for the calculated difference for each of the plurality of compute nodes relative to the calculated differences for the other compute nodes in the plurality of compute nodes, wherein the weighted color value is based on the value of the calculated difference for the respective compute node, the maximum difference value, and the minimum difference value; and

generating a three-dimensional (3D) wireframe image representing the plurality of compute nodes, wherein the 3D wireframe image depicts the plurality of compute nodes and further depicts the calculated difference for each of the plurality of compute nodes, and wherein the 3D wireframe image is colored based on the weighted color value determined for each of the plurality of compute nodes.

16. The non-transitory computer-readable medium of claim **15**, wherein the dedicated hardware performance counters measure a number of network packets injected onto a point-to-point network connecting each of the plurality of compute nodes to one or more neighboring compute nodes.

17. The non-transitory computer-readable medium of claim **16**, wherein the point-to-point network interconnects the plurality of compute nodes to form a multi-dimensional torus.

18. The non-transitory computer-readable medium of claim **15**, wherein the performance counter records a number of floating point operations performed by each of the plurality of compute nodes.

19. The non-transitory computer-readable medium of claim **15**, wherein the performance counter records a number of cache hits/misses that occurs on each of the plurality of compute nodes.

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